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Suspended Sediment Grains Transport in Open-Channel Flow: A Flume-Based Validation of Mixing Length Theory.

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Abstract

The transport of suspended sediment in low-concentration flows is fundamentally governed by flow turbulence generated through basal shear stress. Traditional interpretations of sediment suspension and turbulent mixing have largely relied on the classical mixing-length turbulence theory developed by Prandtl, von Kármán, and subsequent researchers. Although more sophisticated turbulence models have emerged over recent decades, the mixing-length approach remains widely employed in hydraulic engineering, fluvial geomorphology, and sedimentology because of its conceptual simplicity, computational efficiency, and practical applicability. In particular, the theory continues to play an important role in the reconstruction and interpretation of ancient sedimentary environments. Despite its extensive application, the predictive capability of mixing-length theory has not been comprehensively reassessed using modern high-resolution flow measurement techniques. This study therefore evaluates the validity of the classical turbulence-suspension framework through a series of controlled open-channel flume experiments utilizing advanced Acoustic Doppler Velocimeter (ADV) technology. High-frequency velocity measurements were acquired to characterize turbulent flow structures and to assess the correspondence between observed flow behaviour and theoretical predictions. The experimental results demonstrate a strong agreement between measured and model-predicted velocity profiles, indicating that mixing-length theory provides a reliable representation of the time-averaged vertical velocity distribution in turbulent open-channel flows. The findings further confirm the continued usefulness of the theory for estimating basal shear stress and predicting suspended sediment transport under low-concentration conditions. Furthermore, analysis of the velocity data suggests that a von Kármán constant of approximately 0.29 yields a more accurate description of low-concentration sand-laden flows than the conventionally adopted value of 0.41. These results provide new experimental support for the continued application of classical turbulence theory while highlighting the need for revised parameterization in sediment-laden flow systems.

Keywords

Low-concentration flows,
Flow turbulence,
Mixing-length,
Suspended Sediment transport

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Introduction:

Sediment grains are transported in fluvial, coastal, and aeolian environments either as suspended load or bed load depending on grain characteristics such as size, shape, and density, as well as the viscosity and turbulence of the transporting medium. Suspended sediment transport typically involves the movement of fine-grained particles such as fine sand, silt, and clay above the channel bed, where the grains are supported by turbulent flow fluctuations. Naqshband et al. (2017) described suspended sediment grains transport to include the transport of fine sediments such as fine sand, silt, and clays, above the flow bed in intermittent suspension and explained that these fine sediment grains remain in suspension as long as thee bed shear stress exceeds the settling velocity of the grains. In contrast, bed-load transport generally involves coarser particles greater than 0.10 mm in diameter that move intermittently in contact with the bed surface. Bagnold (1956) further noted that the motion of bed-load particles is strongly influenced by gravitational forces and repeated interactions with the channel bed.

The transport of sediment grains is governed by several hydraulic parameters, including time-averaged flow velocity, Reynolds shear stress distribution, and turbulence intensity (Miguntanna et al., 2020; Jain and Ghoshal, 2021). Although sediment transport processes in rivers and streams may appear straightforward, the underlying physical mechanisms are highly complex due to the interaction between turbulence, sediment entrainment, grain settling, and flow structure. Direct measurement of flow properties and sediment transport rates in natural systems, particularly in turbidity currents and sediment-laden flows, remains difficult and in some cases impossible. Consequently, several experimental and numerical models have been developed over the past decades to describe sediment transport processes under a wide range of hydraulic and geological conditions.

Sedimentologists continue to seek reliable and physically based theories capable of accurately predicting sediment transport behaviour and flow properties, especially at the grain scale. Laboratory flume experiments provide an effective and controlled environment for investigating suspended sediment transport processes and evaluating turbulence models. Flume-based investigations allow precise regulation of hydraulic variables such as discharge, flow velocity, flow depth, channel slope, and sediment grain size while enabling detailed observation of sediment entrainment, suspension, transport, and deposition processes that are difficult to quantify in natural systems.

The development of physically based sediment transport theory has evolved through several important contributions. Kramer (1935) identified four transport conditions ranging from no transport to general transport depending on the intensity of sediment motion. Shields (1936) pioneered the concept of sediment entrainment threshold and demonstrated that suspension occurs when local bed shear stress exceeds a critical value. Rouse (1937) later developed one of the most widely used equations for predicting suspended sediment transport in steady uniform flow, although the assumptions required for its application are rarely fully satisfied in natural environments. Einstein and Chien (1955) modified the logarithmic velocity distribution law to account for the influence of suspended sediment particles on momentum exchange in sediment-laden flows. Bagnold (1956) developed quantitative relationships for both bed-load and suspended-load transport based on stream power concepts, while Bagnold (1966) further proposed that sediment grains remain suspended when upward turbulent velocity fluctuations exceed the downward settling tendency of the particles. Bennett and Best (1995) demonstrated that turbulence and time-averaged velocity distributions near the bed are closely linked to sediment suspension processes. Subsequent investigations by Niño and Garcia (1998), Lee and Hsu (1996), Schmeeckle et al. (2001), and Mazumder et al. (2008) further examined grain lift-off, particle trajectory, collision dynamics, and the influence of turbulence on sediment transport.

A major contribution to turbulence theory was made by Prandtl (1925), who introduced the Mixing Length Theory to estimate Reynolds shear stress in turbulent flows. The theory describes the exchange of momentum between fluid layers and predicts the distance over which fluid particles retain their momentum characteristics before mixing with the surrounding flow. Von Kármán (1930) later refined the theory through the introduction of the similarity hypothesis. Despite its widespread application in sediment transport studies, the theory has historically been difficult to validate experimentally due to limitations in measuring instantaneous turbulent velocity fluctuations. Prandtl (1925), O'Brien (1933), von Kármán (1935), and Bagnold (1966) all acknowledged these technical limitations.

Subsequent studies identified several limitations in applying Mixing Length Theory to sediment-laden flows. Itakura and Kishi (1980) observed that the logarithmic velocity distribution does not adequately describe all sediment-laden flow conditions, while Umeyama and Gerritsen (1992) demonstrated discrepancies between theoretical predictions and experimental observations outside the near-bed region. More recent studies have proposed alternative turbulence and basal shear stress models (Parker, 2008; Absi, 2011; Castro-Orgaz et al., 2012; Schmeeckle, 2014; Hill et al., 2017), although many of these approaches remain limited by the inherent uncertainty associated with turbulence behaviour in natural flows.

This study investigates suspended sediment transport in open-channel flow through controlled laboratory flume experiments aimed at evaluating the applicability of Mixing Length Theory to sediment grain transport processes. Particular emphasis is placed on the relationship between turbulent flow characteristics and the vertical distribution of suspended sediment concentration under varying hydraulic conditions. Experimental measurements of flow velocity and suspended sediment concentration are compared with theoretical predictions derived from Mixing Length Theory to assess the theory's effectiveness in representing turbulent sediment diffusion and suspension dynamics.

The study further examines the vertical streamwise velocity structure of turbulent clear-water flows based on the original formulations proposed by Prandtl (1925), von Kármán (1930), O'Brien (1933), and Bagnold (1966). Modern Acoustic Doppler Velocimeter (ADV) technology is employed to capture high-resolution velocity fluctuations and turbulence characteristics within the flume system. Through this experimental approach, the study evaluates the continuing relevance and practical applicability of Mixing Length Theory in sediment transport research.

The significance of this research extends beyond hydraulic engineering into broader sedimentological and geomorphological applications. Improved understanding of suspended sediment grains transport processes contributes to more accurate interpretation of sedimentary environments, prediction of sediment deposition patterns, and modelling of fluvial and alluvial systems. Furthermore, the findings may enhance sediment transport models used in river engineering, erosion control, environmental management, channel restoration, and sedimentary basin analysis. The paper begins by outlining the theoretical framework and governing equations associated with turbulence and suspended sediment transport. This is followed by a description of the experimental setup, instrumentation, and data acquisition procedures used in the laboratory flume experiments. The experimental results are subsequently analysed and compared with theoretical predictions in order to evaluate the applicability of Mixing Length Theory in describing turbulent suspended sediment transport processes.

Theory:

The theory outlined below relates to a steady, uniform flow and is therefore applicable in cases where this is a reasonable approximation such as in a river channel (or the body of a long-duration turbidity current) where the width, gradient and direction are slowly varying.

By definition, a uniform flow has a constant thickness throughout and, as a consequence, the flow top has a slope equal to that of the bed floor across which it travels. Furthermore, in a steady flow, there is no acceleration and so friction forces at the base of the flow are exactly balanced by the component of the flow's weight along the sloping base. Hence, for a steady, uniform current

$$\tau_b = -\Delta\rho\, h\, g\, s \qquad (1)$$

Where τ_b is basal shear stress, *h* is the flow thickness, $\Delta\rho$ is the density excess of the flow, *g* is the acceleration due to gravity and *s* is the gradient. More generally, similar force balances must exist within the flow itself, i.e. there are internal shear forces of the form

$$\tau_b = -\Delta\rho\, z\, g\, s \qquad (2)$$

where τ is produced by shearing between water layers and *z* is distance from the flow top. In turbulent flows these internal forces are balanced by Reynold's stresses or eddy stresses and momentum conservation arguments then lead to the result that (Reynolds, 1895)

$$\tau_b = -\rho\overline{u'w'} \qquad (3)$$

where ρ is the flow density, u' is the turbulent fluctuation of velocity in the direction of flow and w' is the turbulent velocity fluctuation in the vertical direction. Throughout this paper, over-bars indicate time-averaging. The velocity fluctuations, in turn, are defined by

$$u = \bar{u} + u',\ v = \bar{v} + v'\ \&\ w = \bar{w} + w' \qquad (4)$$

Where u, v and w are the flow velocities in the *x*, *y* and *z* directions.

Combining equations (2) & (3) then gives

$$\overline{u'w'} = z\, g'\, s \qquad (5)$$

where g' (=$g\Delta\rho/\rho$) is known as the reduced gravity.

We can now introduce a shearing velocity, u_*, defined by

$$\tau_b = \rho u_*^2 \qquad (6)$$

This simply recasts the basal friction of the flow in terms of a parameter with the dimensions of velocity but, as we'll see, this is a useful transformation. It follows from equations (1), (3) and (6) that

$$u_*^2 = hg's. \qquad (7)$$

and

$$u_*^2 = \overline{u'w'}_0 \qquad (8)$$

Mixing length theory also utilizes u_* and predicts a logarithmic velocity profile in turbulent flows (the "law-of-the-wall") given by

$$u = (u_*/\kappa)\ln(Z/z_0) \qquad (9)$$

where k is von Karman's constant, Z is distance above the flow base and z_0 is a constant related to the roughness at the flow-base.

The final component of theory relates the velocities discussed above to grain suspension. Turbulent suspension occurs due to the vertical velocity fluctuations, near the flow base, which exceed the fall velocity (Bagnold, 1966). Characterizing these fluctuations by their root mean square (RMS) value then gives a suspension criterion of

$$\sqrt{\overline{w'^2}_0} \gtrsim U_{fall} \qquad (10)$$

where U_{fall} is the fall speed of the particles under consideration.

However, in an un-instrumented flow, the RMS velocity fluctuations are not known, and the assumption is usually made that turbulence is approximately isotropic so that

$$\overline{w'^2} \approx \overline{u'w'}. \qquad (11)$$

and hence, from equation (8),

$$U_{fall} \lesssim u_*. \qquad (12)$$

Method

Experimental Description:

Although the theory outlined above is well established and similar approaches have long been applied in the study of sediment transport processes, its experimental validation using modern measurement technology remains limited. Bagnold (1966), for instance, emphasized the difficulties associated with accurately measuring turbulent velocity fluctuations at the time. With the development of advanced acoustic flow-measurement technologies, it is now possible to obtain high-resolution turbulence data. This study therefore employs modern acoustic instrumentation to experimentally examine and evaluate several key aspects of the aforementioned theory.

The flume tank facility

The experimental facility was located at Sorby Fluid Dynamics Laboratory at the University of Leeds. The facility includes a tilting rectangular glass-sided flume, 8.5m long, 0.34m deep and 0.30m wide (Figures 1a and b), which provided clear view of the flow and allowed high-speed photography as well ease in taking measurement. The other parts of the flume, particularly the frames, were made of corrosion resistant steel (see Figures 1b-c).

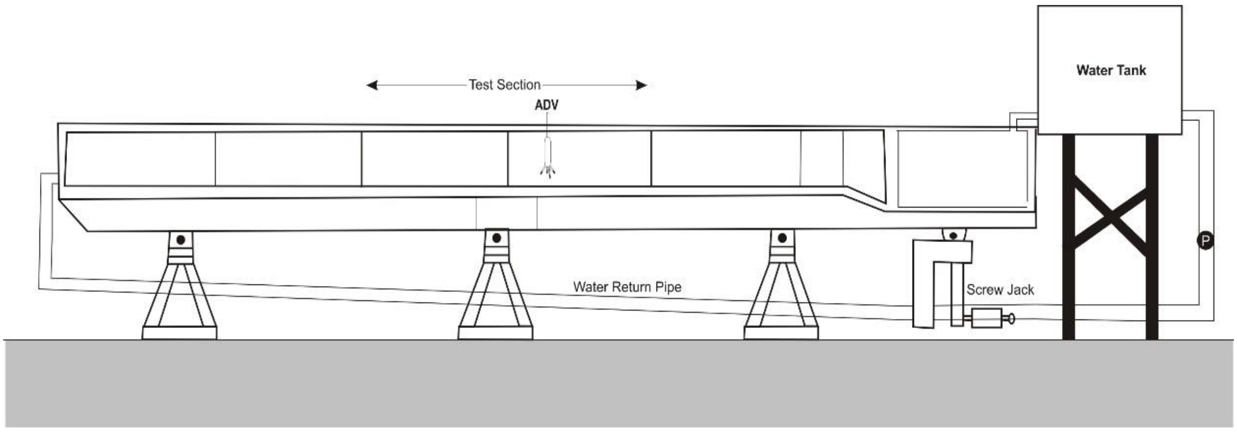

Figure 1a; Schematic diagram of the laboratory flume tank used in this research.

Figure 1b; Photograph of the open channel recirculating laboratory flume tank used in this research.

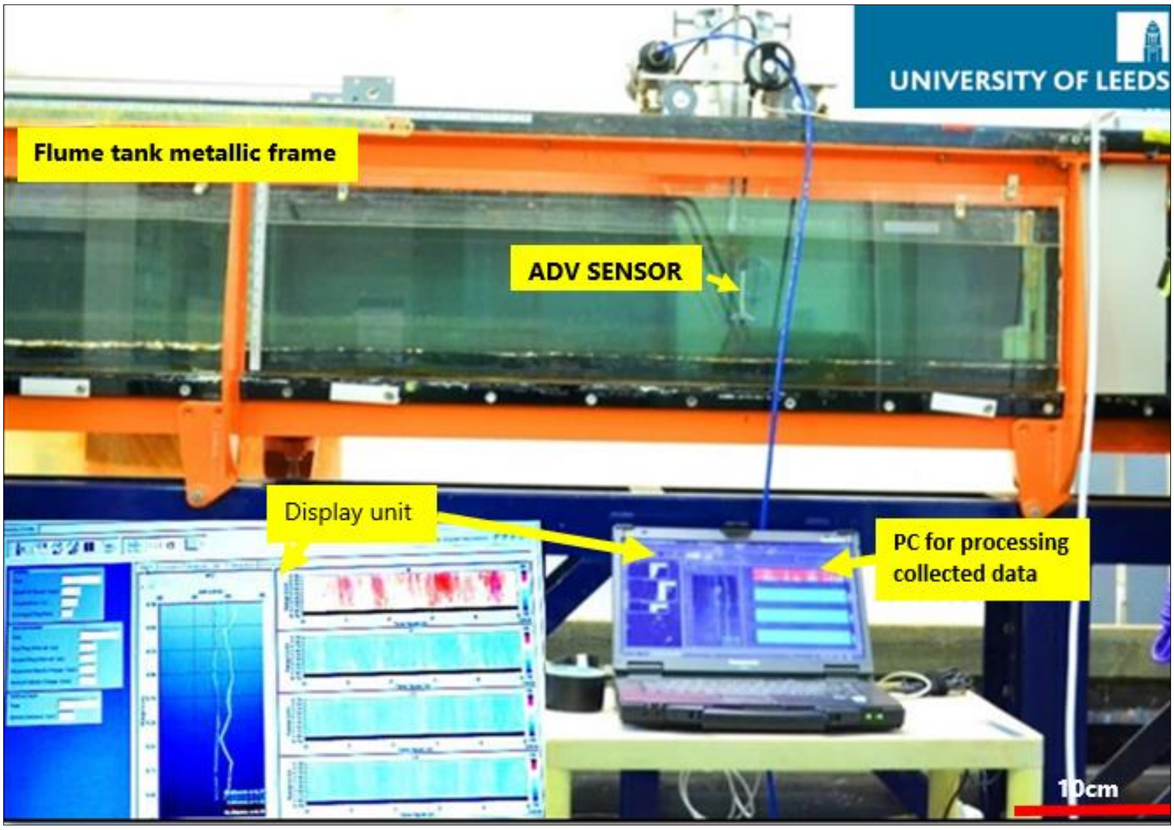

Figure 1c: The Flume (The Measurement and Observation section as well as the instrumentation).

A Hydrostat centrifugal pump was fitted to the flume tank to drive clear water into the flume which was recirculated through the flume via a return PVC pipe of 0.20 m diameter, placed below the flume tank. The re-circulating flume was necessary to maintain uniform flow of water circulation in the flume. The flow discharge rate into the flume tank was monitored using an ABB electromagnetic flow meter which was controlled via an inverter control unit which governed the discharge rate and flow velocity. A pack of stainless-steel pipes of 2.50 cm radius were placed at the upstream end of the flume tank to prevent an occurrence of vortex flow. Water temperature was an average of 20±2 ^{0}C.

The flume was instrumented with a three-dimensional (3-C) Acoustic Doppler Velocimeter (ADV) measuring system, which was positioned on the centre of the flume, about 4.2m from the downstream end of the flume and all measurements taken at the centreline of the cross section.

Six experimental cases were designed for the flow experiment with unique conditions such as varying discharge rate, flow height/thickness, type of flume floor (roughness) as well as the slope of the flume.

The experiment began with clear water being pumped from an overhead tank into the flume and allowed to recirculate until a uniform steady flow was achieved. Care was exercised to avoid possible hydraulic jump/vortex flow occurring along the flow path and especially at the upstream end of the flume by maintaining a suitable discharge rate. A hydraulic jack beneath the flume was used to tilt the flume and adjust the slope of the flume.

The initial flow speed was calculated from the volumetric discharge with respect to the cross-sectional area. This was varied for the different experimental flow cases. An outline of the flow condition is listed in Table 1 below.

Table 1: Summary of flow conditions for the cases investigated

Flow conditions	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**
Bed Character	Finer-grained beds	Finer-grained beds	Coarser-grained beds	Coarser-grained beds	Coarser-grained beds	Coarser-grained beds
Flow height to roughness (m)	0.92	0.18	0.192	0.192	0.14	0.14
Flow area (m^2)	0.058	0.054	0.058	0.058	0.042	0.042
Flume average slope	0.053	0.071	0.079	0.088	0.132	0.141
Mean discharge rate (l/s)	21.6	39.6	24.6	31.3	21.6	33.19
Mean discharge rate (m^3/s)	0.022	0.04	0.025	0.031	0.022	0.033
Mean flow velocity (m/s)	0.36	0.551	0.333	0.512	0.443	0.616

The Acoustic Doppler Velocimetry

The Acoustic Doppler Velocimeter (ADV) is one of the most advanced instruments currently available for measuring flow velocity and turbulence characteristics in hydraulic experiments (Rowiński et al., 2005; Pope et al., 2006). Unlike earlier ADV systems that employed three receivers, the ADV used in this study, the Vectrino-II profiler, is equipped with four probe heads consisting of four receivers positioned along the *x, y,* z_1 *and* z_2 directions. Beams 1 and 3 measure downstream *(u)* and vertical *(z)* velocity components, while beams 2 and 4 record cross-stream *(v)* and vertical *(*z_2*)* velocities.

The inclusion of a fourth receiver significantly improves measurement accuracy by enabling the instrument to simultaneously record two independent vertical velocity components. This enhancement also permits data acquisition at higher sampling frequencies, up to 100 Hz, without compromising data quality. The experiments utilised the latest version of the Vectrino profiler ADV (Vectrino-II), which was configured to simultaneously measure flow velocities at 17 discrete sampling points located at varying distances from the transmitter for each selected probe position.

The probe was mounted vertically beneath the transducer and oriented perpendicular to the flume bed. These 17 sampling positions were used to generate multiple overlapping vertical velocity profiles, allowing the construction of a continuous time-averaged velocity profile covering most of the water column. Velocity measurements were obtained by moving the Vectrino profiler in 10 mm vertical increments, beginning at 50 mm above the bed surface and continuing upward until interference from the free water surface affected the transmitter signal. At each measurement location, velocity data were sampled at a frequency of 100 Hz for a duration of 300 seconds.

According to Chanson et al. (2007), raw ADV measurements do not accurately represent true turbulent flow characteristics unless the data undergo appropriate post-processing procedures to remove spikes, Doppler noise, and sampling-related filtering effects. Consequently, all acquired velocity data in this study were post-processed by the University of Leeds Sorby Laboratory research team using an advanced intelligent correlation-threshold filtering technique. This processing method incorporated both a phase-unwrapping algorithm and a phase-space threshold despiking filter to improve data reliability and turbulence resolution (see Thomas and McClelland, 2015, for further details).

Results and discussion

In this section, a summary of the experimental results and analysis are presented. This is followed by a discussion of the analytical results.

Velocity-depth profiles

Velocity profiles for all six clear water flow cases as computed based on averaging of the instantaneous velocity measurements are presented in Figure 2 below. The profiles show a velocity maximum near the water surface and a velocity minimum near the base of flow.

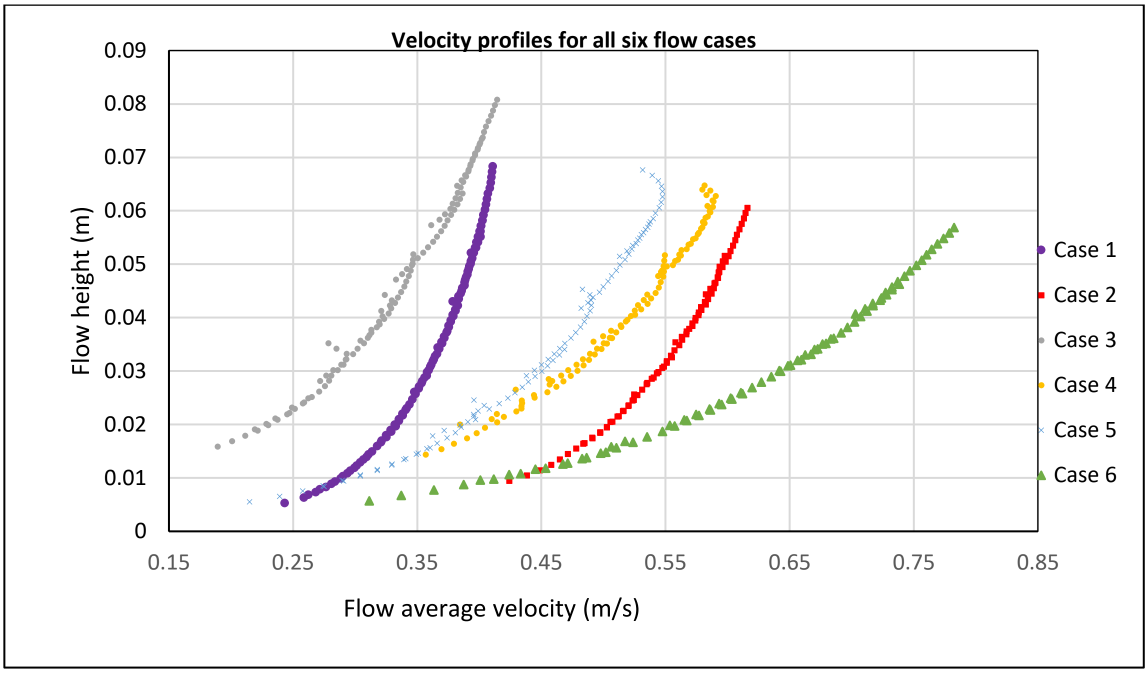

Figure 2. Vertical velocity profiles relative to flow height for flow cases 1-6.

Measured and modelled flow velocities

Experimentally derived mean flow velocity data were matched with modelled velocities to determine how well both data agree as presented in Figure 3. A regression statistical analysis using excel analytical tool confirmed a significant positive relationship between both velocities. Regression statistical analysis was further done including the R-squared and P-values for all six flow cases and results presented in table 2 below.

Table 2: Summary of Regression statistics of velocity data for all six flow cases

Regression statistics	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Observations	112	85	112	110	96	80
Multiple R	0.99978	0.99962	0.997	0.995893	0.997855	0.999677
R-squared	0.99955	0.99925	0.99402	0.991802	0.995715	0.999354
Standard Error	0.00086	0.00127	0.00443	0.005615	0.005598	0.003029
P-value	3.10E-18	2.10E-131	3.80E-124	4.80E-104	4.10E-113	3.70E-126

Modelled velocities were derived using the Law-of-the-Wall approach. Flow velocities measured at different heights above the bed were plotted against flow height, and a regression fitting procedure was applied to the resulting data. Estimates of shear velocity and bed roughness length were then obtained from the slope and intercept of the fitted regression equation. A von Kármán constant of $\kappa = 0.29$ was adopted, as this value provided the best fit to the observed velocity profile data.

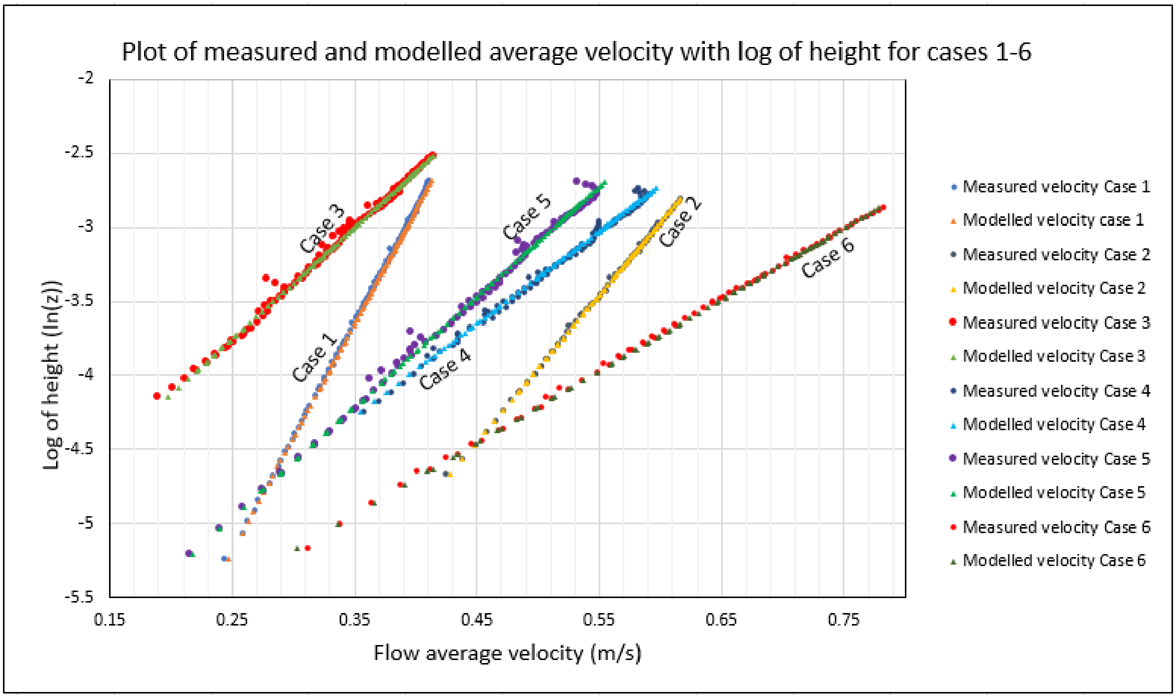

Figure 3: Comparing basal shear stress estimates from LoW and RSS.

Reynolds stress validation

Equation (3) predicts that a plot of $\overline{u'w'}$ against height above base of flow should be a straight line such that an intercept of $\overline{u'w'}$ goes to zero. Figure 4 shows measurements of $\overline{u'w'}$, from the flume tank, and how they vary with height and how the Reynolds shear stress, $\overline{u'w'}$ for each flow case align to a straight line. The corresponding value @ h=0 also gives the Reynolds Basal Stress (Pa) at base of flow $\overline{u'w'}$. These results also confirm that the Reynold's stresses increase with depth as a consequence of the increased weight of the overlying water.

Table 3 below shows the comparison of Reynolds shear stress estimates from both calculated and derived from as inferred from base of flow.

Table 3: Comparison of calculated and predicted Reynolds shear stress estimates

Flow cases	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Reynolds Basal Shear Stress (Pa) at base of flow(<u'w'>) @h=0	0.48	0.9	0.88	2.02	1.39	3.1
Calculated Basal Reynolds Stress (<u'w'>)	0.429	0.948	0.889	2.067	1.144	3.008

These results show similarity in the Reynolds stress calculated as well as that estimated from base of the flow as all data points align to a reasonable extent to a straight line as predicted by the theory.

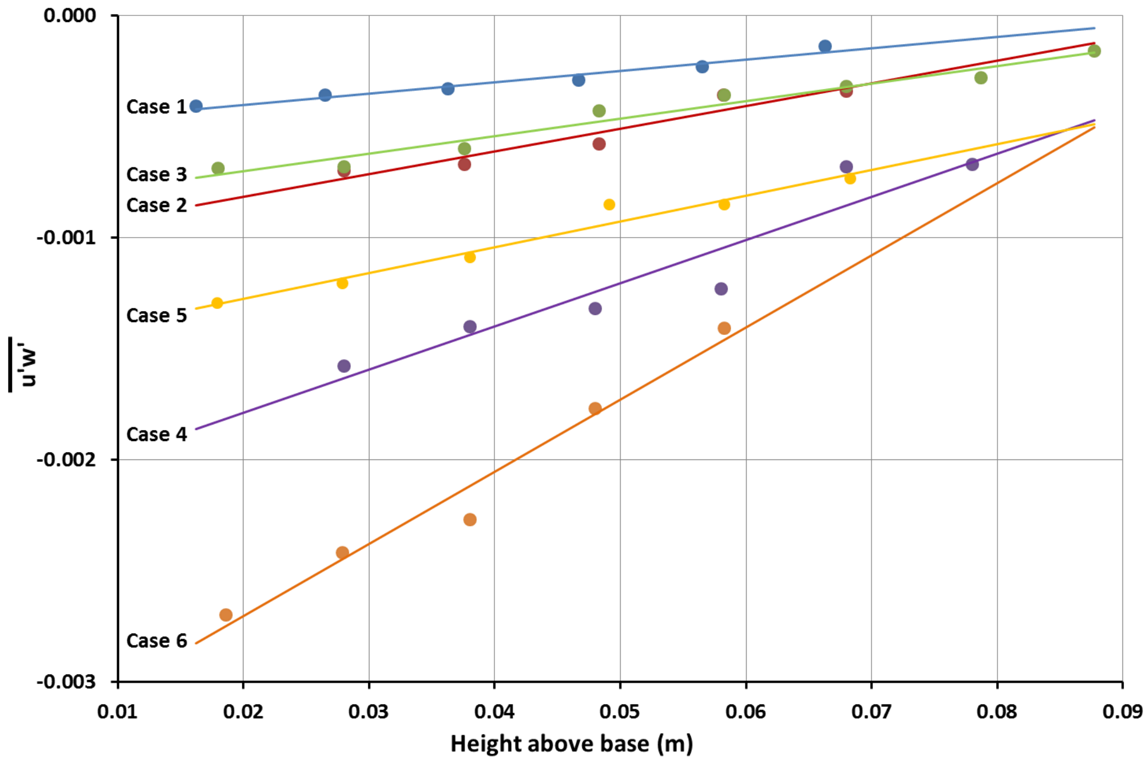

Figure 4: Variation in Reynolds stress with height in the 6 flume-tank experiments. Equation (3) predicts that these should be straight lines.

Law-of-the-Wall validation

From equation (9), the Law-of-the-Wall predicts that a plot of $\bar{u}$ against (z) should be a straight line. Figure 4 shows very good agreement with this expectation. Also, as shown in the figures, model predictions such as the mean velocities are observed to be consistent with measured values as both are well aligned on the straight line. This good agreement between modelled and measured parameters confirms the validity of the Law-of-the-Wall in predicting flow parameters such as mean and shear velocity.

Furthermore, equation (9) implies

$$u_* = \kappa. \text{ Gradient} \quad (13)$$

and

$$\text{Ln } (z_0) = \text{Intercept / Gradient} \quad (14)$$

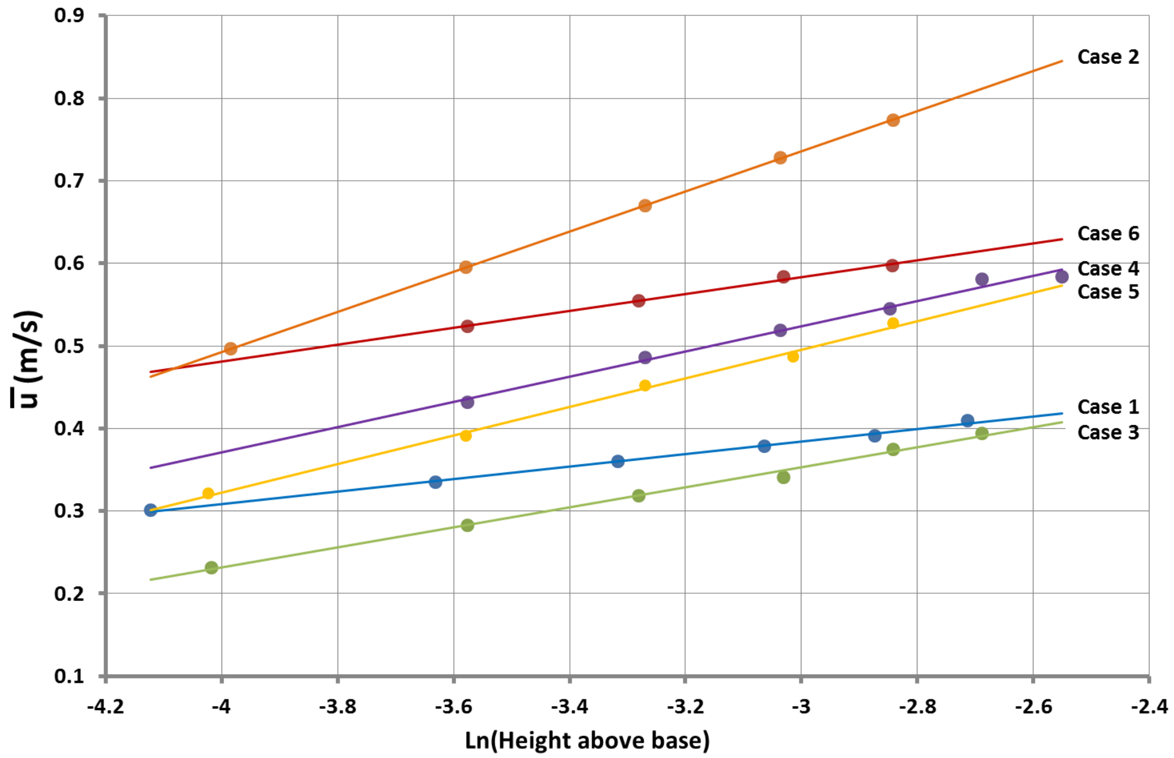

Figure 5. Testing the law of the wall (equation (9)). Excellent fits to straight lines for all cases suggest that this is a good approximation

Shear velocity is thus estimated from equation (13) and shear stress determined. However, estimates of roughness, from equation (14), are also of interest. It is expected that rougher floors should have higher values of z_0 and consequently, greater turbulence. To test this, the roughness length, z_0, was estimated from the log-profile method, through a best fit and by adjusting κ to a value of 0.29 (to minimise the difference between the basal stress from Law-of-the-Wall and the Reynolds stress (see figure 5). Clearly, from the results, coarser-grained beds have a higher z_0 than finer-grained beds and there is a clear dichotomy between the coarser-grained beds cases with z_0 ~ 0.002 m and the finer-grained beds-base case with z_0 ~ 0.0001m. However, these results also show that roughness elements, x, is greater than the roughness length, z_0, which interestingly confirms Raudkivi (1998).

Validation of the mixing-length turbulence theory

Basal shear stress estimates obtained using traditional methods are theoretically expected to produce similar values. In practice, however, the estimates often differ considerably, and no consistent trend can usually be identified. The turbulence-suspension theory discussed earlier provides three principal approaches for determining basal shear stress, based respectively on Equations (1), (3), and (6). The first approach, commonly referred to as the slope method, requires only measurements of flow slope, fluid density, and flow thickness.

The present study, however, focuses on the other two approaches: the *Reynolds stress method*, which requires measurement of velocity-fluctuations and extrapolating the linear distribution of $\overline{u'w'}$ to the base of the turbulent flow. In contrast, the Law-of-the-

Wall approach estimates basal shear stress by extrapolating the mean velocity profile to the bed using the logarithmic velocity distribution. According to the von Kármán–Prandtl turbulence-suspension theory, these two methods should produce comparable estimates if the theory accurately represents the suspension and transport of sediment grains.

Application of the Law-of-the-Wall method requires specification of the von Karman's constant, κ. Here, we make no assumption concerning the value of κ but, instead, the gradient obtained from Figure 5 was plotted against the Reynolds stress extrapolated to the base of the turbulent flow. If equations (3) and (6) give equivalent estimates of shear velocity, u_* then the result should have a gradient equal to 1/κ. The resulting correlation was statistically significant at a significance level of 3.8% and produced an estimated von Kármán constant of: κ =0.29±0.05

This value is consistent with previously reported estimates, including those of Wang and Larsen (1994), κ =0.16; Einstein and Chien (1955), κ = 0.168-0.406; Vanoni and Nomicos (1960) κ = 0.209-0.384; and Gust and Southard (1983) κ = 0.28). Notably, all of these experimentally derived values are substantially lower than the conventionally assumed range of 0.40–0.41 commonly adopted in sediment transport studies (Felix et al. 2006; Baas et al. 2009, 2011; Darby and Peakall 2012; Dorell et al. 2014; Yin et al. 2016)

Using the experimentally determined value of κ, the basal shear stress estimation methods produced the results presented in Figure 6.

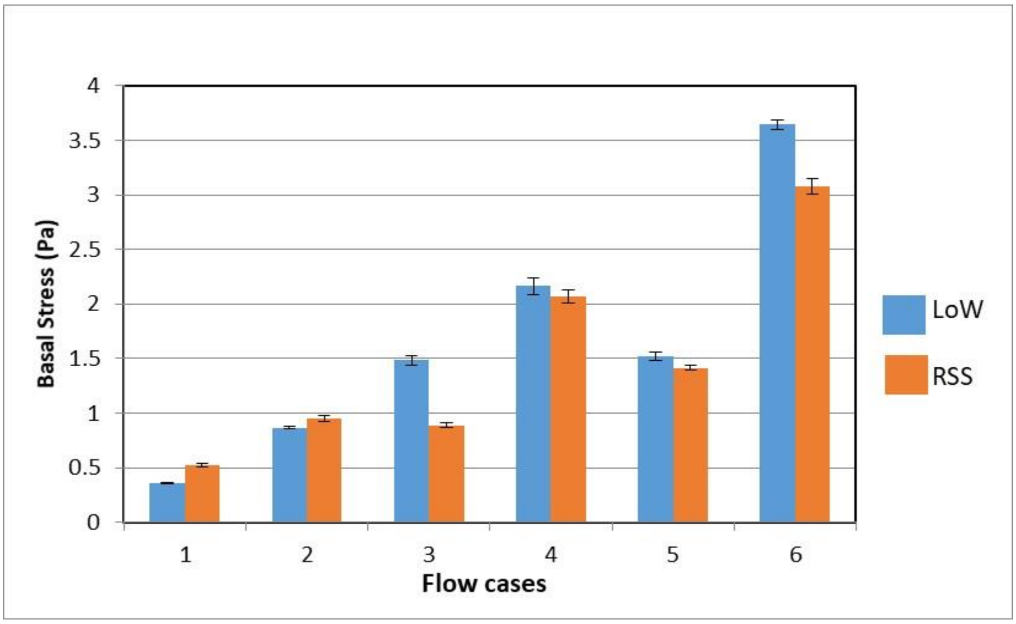

Figure 6: Comparing basal shear stress estimates from LoW and RSS.

The results demonstrate that both methods employed produced broadly comparable estimates of shear velocity despite the previously identified issues associated with flow non-uniformity. Although the agreement between the methods is not exact, the estimates are of the same order of magnitude, indicating a reasonable level of consistency among the different approaches. This consistency provides confidence that shear stress values obtained from either method can serve as acceptable first-order approximations of the eddy stresses acting near the bed of the flow.

Similar observations were reported by Rowiński et al. (2005), who noted comparatively higher shear stress estimates obtained from the logarithmic profile method in their experimental investigations. In the present study, the relatively lower Reynolds stress estimates may be attributed to measurement uncertainties associated with instrument sensitivity. The Reynolds stress method is highly sensitive to sensor alignment, making the resulting estimates susceptible to errors arising from improper positioning of the measuring instrument within the flow field. An important observation from the experiments is that the higher shear stress estimates derived from the logarithmic profile method were consistently associated with flows over coarser-grained bed surfaces. The exact reason for this systematic increase remains unclear; however, it suggests that bed roughness may exert a significant influence on velocity profile development and turbulence structure.

In contrast, flow Cases 1 and 2, which were conducted over fine grained sediment surfaces, produced comparatively lower logarithmic profile estimates relative to the Reynolds stress method, with differences of approximately −45.6% and −9.6%, respectively. Furthermore, flow Cases 1, 2, 4, and 5 exhibited strong agreement between the methods, with differences in shear stress estimates generally less than 9.7%.

The choice of a von Kármán constant value of κ = 0.29 in this study was achieved through manual adjustment in order to minimise discrepancies between the Law-of-the-Wall predictions and Reynolds stress estimates. As expected for a theory intended to approximate the highly complex nature of turbulent flow behaviour, the agreement between the Law-of-the-Wall and Reynolds shear stress estimates is not exact. Nevertheless, the correspondence between the two approaches can be regarded as sufficiently good for practical applications. Consequently, shear stress estimates obtained from either method may be considered reasonable first approximations of the eddy stresses acting at the base of turbulent open-channel flows.

Conclusion

This laboratory flume study has provided a controlled framework for investigating suspended sediment grains transport processes and evaluating the applicability of turbulence-based sediment transport theories. Although the mixing-length (turbulence–suspension) theory is not a complete or highly precise representation of flow turbulence, the central issue has always been the extent to which it provides a sufficiently accurate approximation to be practically useful.

Despite the availability of more sophisticated and modern theories of turbulent sediment transport, the relative simplicity of mixing-length approaches continues to make them particularly valuable for estimating flow properties in ancient sedimentary systems. Given their continued application in sedimentological studies, it has been important to assess whether these theories remain valid when tested using modern flow-measurement techniques that were not available when the original formulations were developed.

This research has demonstrated that the turbulence–suspension theory remains highly relevant for describing flows under both assumed uniform and non-uniform conditions, at a level of detail not previously investigated. The theory provides a robust framework for predicting vertical velocity profiles, with the time-averaged velocity distribution being well represented by the von Kármán turbulence model.

The findings indicate that, within steady and uniform water flows, shear stresses are, to a reasonable approximation, balanced by the eddy stresses predicted by Reynolds' turbulence theory. Furthermore, the shear velocity values obtained were found to provide reliable estimates of the vertical root-mean-square (RMS) velocity fluctuations near the flow boundary. These results support the continued use of turbulence-based approaches for characterising flow behaviour and sediment suspension processes in open-channel flows.

In addition, the results strongly support previous studies suggesting that the von Kármán constant may be significantly lower than the conventionally adopted value of 0.41 under certain flow conditions. Based on the present investigation, a value of $\kappa = 0.29$ is recommended for low-concentration sand-laden flows, as it consistently provided the best fit to the observed velocity profile data.

Overall, the study confirms that the underlying assumptions of mixing-length theory provide a reasonably accurate representation of flow behaviour in sediment-laden open-channel flows. Consequently, sedimentologists can continue to apply this theoretical framework with confidence when estimating basal shear velocities and interpreting the transport and deposition of suspended sediments in both modern and ancient sedimentary environments.

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